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Generator absorber heat exchange based absorption cycle—A review

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ABSTRACT

GAX based absorption cooling systems have been investigated in recent years by various groups across the world due to their advantage of offering a higher performance compared to that of the conventional ammonia–water absorption systems. In this paper, a comprehensive review of several different GAX cycle configurations has been explained in detail. The choice of working fluids and the performance of the GAX cycle in terms of coefficient of performance and temperature lift are also presented. The study reveals an improvement in the COP of about 10–20%, 20–30% and 30–40% in absorber heat recovery cycle, simple GAX and branched GAX cycle respectively, than that of a conventional single effect system for the same set of operating conditions. The importance of the GAX cycle with respect to the current energy scenario is also highlighted.

Contents

Abbreviations: A, absorber; ABSIM, absorption simulation; AHX, absorber heat exchanger; ASP, additional solution pump; C, condenser; CO, compressor; COP, coefficient of performance; CPC, condensate pre-cooler; DAHX, desorber/absorber heat exchange; E, evaporator; EV, expansion valve; EXP, experiment; G, generator; GAX, generator absorber heat exchange; GAXA, GAX absorber; GAXD, GAX desorber; GFD, gas-fired desorber; GHX, generator heat exchanger; HCA, hydronically cooled absorber; HGAX, hybrid GAX; HRA, heat recovery absorber; HTG, high temperature generator; LFRC, linear fresnel reflector concentrator; LTG, low temperature generator; M, mixer; PGAX, GAX cycle for panel heating; PRV, pressure reducing valve; PSE, single effect cycle for panel heating; RE, rectifier; SCA, solution cooled absorber; SCRE, solution cooled rectifier; SHD, solution heated desorber; SHX, solution heat exchanger; T, theoretical; TR, tons of refrigeration; VX GAX, vapour exchange generator absorber heat exchange; WCRE, water cooled rectifier; WGAX, GAX cycle for waste heat recovery; WHX, waste heat exchanger.

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Nomenclature

Q	heat load (kW)
UA	overall heat transfer conductance (W/K)

1. Introduction

Ever since Molina and Rowland [1], whose work led to the Montreal protocol [2], proved the adverse effect of CFCs on the ozone layer, the search for alternatives to CFCs became an urgent need among the research community in the HVAC sector. The Kyoto protocol [3] has urged nations to mitigate the negative effect of green house gases and other chemicals on planet earth. HVAC [4] systems are the major consumers of power and this increases the carbon foot prints. Heat operated absorption systems are considered to be a promising alternative and a potential replacement for vapour compression refrigeration systems to overcome these issues. Currently, environmentally friendly fluid pairs such as ammonia–water and water–lithium bromide are used as working fluid pairs [5,6] in the absorption systems. In the water–lithium bromide system, water is the refrigerant and lithium bromide is the absorbent. However, due to freezing issues, water is not a suitable refrigerant for low temperature applications. Alternatively, the ammonia–water absorption system is widely used for a wide range of low temperature applications. Even though the COP of an absorption system is less when compared to that of the vapour compression system, its ability to utilize waste heat and low grade energy has made these systems an attractive option. In recent years, ammonia/water absorption heat pump and refrigeration new cycles have gained an ever rising interest in the fields of biomass [7,8], solar energy [9,10] and waste heat [11]. It is learnt that every design change in these system has resulted in an improvement of the COP and yielded a great benefit in energy consumption. There are several ways by which the performance of an absorption system could be improved. Apart from the conventional single effect systems [12,13], the double effect systems [12,14], multi-effect systems [13,15], hybrid absorption systems [16–19] and generator absorber heat exchange (GAX) systems [20–60] are the major classifications of the absorption system. The pioneering works on the GAX system are classified under different types and some important inferences from the papers are highlighted.

2. Single effect system

The conventional single effect absorption cooling system is shown in Fig. 1. In a vapour absorption system, the compressor is replaced by an absorber generator assembly. The low pressure refrigerant vapour from the evaporator is fed into the absorber, which releases heat to the surroundings due to exothermic reaction. The weak solution is then pressured using a solution pump and fed into the generator through a solution heat exchanger. The high pressure solution is heated by an external heat source in a generator which drives off the refrigerant vapour to the rectifier. The strong solution returns from the generator and enters the absorber through a solution heat exchanger. The solution heat exchanger is used to transfer heat from the strong solution to the weak solution, which improves the COP of the system. In order to remove the water vapour from the fluid stream at the exit of the generator, a rectifier is employed. Further, the refrigerant enters the condenser and the refrigerant liquid is expanded in the expansion valve before it produces the cooling effect in the evaporator. The possibility of recovering the internal heat in the basic single effect absorption cycle, with a wide solution concentration interval, was described at the beginning of the century by Altenkirch [20].

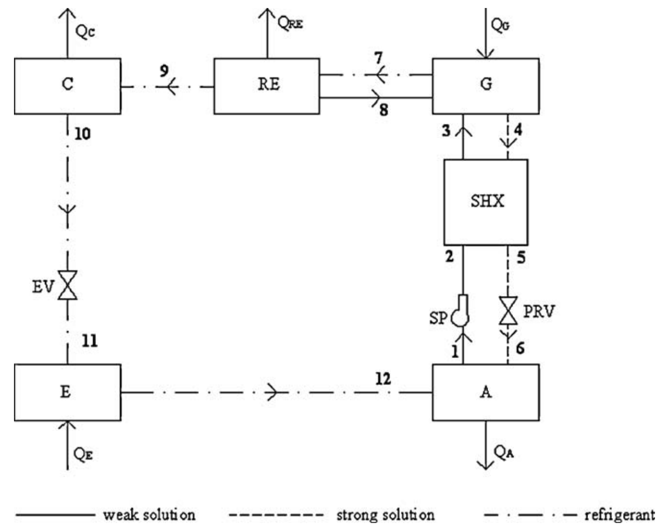

Fig. 1. Schematic of single effect absorption system.

3. GAX cycles—a classification

3.1. Simple GAX cycle

A simple GAX cycle is shown in Fig. 2a and b. The solid and dotted lines represent a GAX cycle and single effect cycle, respectively. In the absorber and generator, the pressure and concentration are maintained in such a way as to cause a temperature overlap between the absorber and the generator. This provides the possibility that some of the heat of absorption may be rejected to the generator within the cycle, leading to a higher COP. This overlapping of heat is an attractive characteristic of the GAX cycle using ammonia–water, which cannot be realized in the water–lithium bromide absorption cooling systems.

Priedeman and Christensen [21] presented a general ammonia–water absorption heat pump cycle design of capacities 3, 3.3 and 5 TR that was modeled and tested. The experimental results were used to validate the cycle simulation. The 5 TR capacity chiller that was modeled using the ABSIM – OSU software [22], which is a modular computer code used for the simulation of an absorption system, showed a 5% difference in the COP between the simulated and experimental findings.

Velázquez and Best [23] reported the thermodynamic analysis of a 10 kW air-cooled GAX system as shown in Fig. 3, operated with hybrid natural gas and solar energy. The COP was found to be 0.86 for cooling and 1.86 for heating together with an internal heat recovery of 16.9 kW. The efficiency of the system decreases as the temperature lift (temperature difference between the condenser and evaporator) increases. The system was found to be an excellent option for air conditioning purposes where the temperature lift was small.

Garimella et al. [24] studied the performance of a GAX heat pump in both heating and cooling modes by using OSU – ABSIM software. The variables that affect the system performance were systematically investigated over a wide range of ambient temperatures. The COP of the cooling and heating modes was 0.925 and 1.51 respectively, for an ambient of 35 and 8 °C.

Grossman et al. [25] investigated the performance of a GAX heat pump for both the heating and cooling modes by using ABSIM software for various operating conditions. It was inferred that the

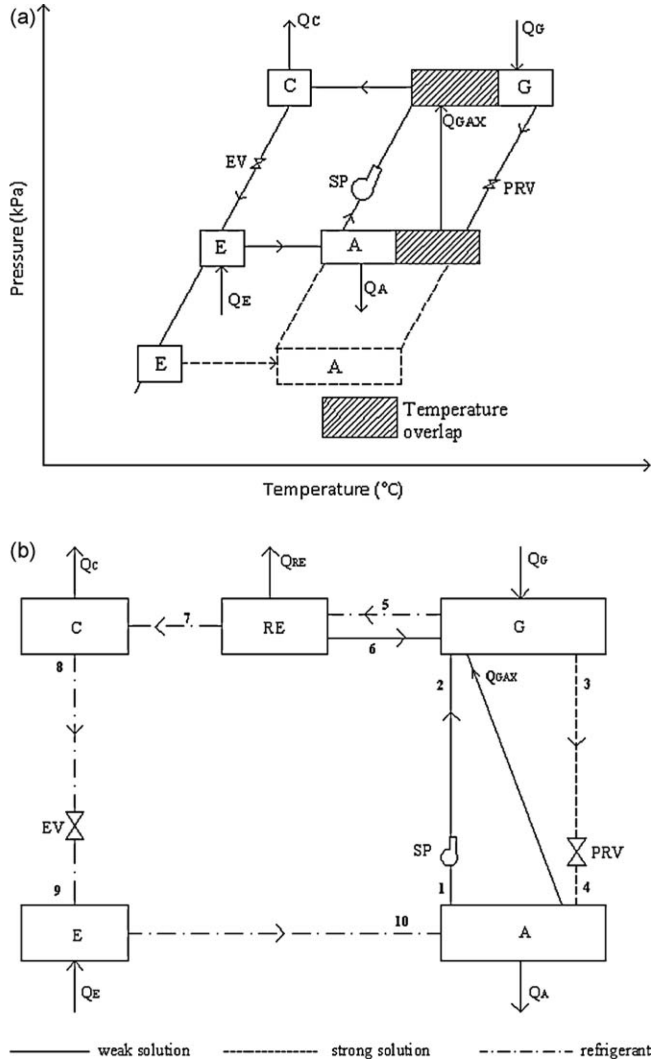

Fig. 2. (a) Schematic of simple GAX cycle–temperature overlap [35]. (b) Schematic of simple GAX cycle [12].

rectifier could produce distilled refrigerant vapour with 99% concentration over the entire range of heat rejection temperatures. The influence of some of the design parameters, such as the flow rate in the GAX heat transfer loop, and several flow controlling methods was also investigated. A cooling COP of 1.0 and a heating COP of 2.0 were obtained.

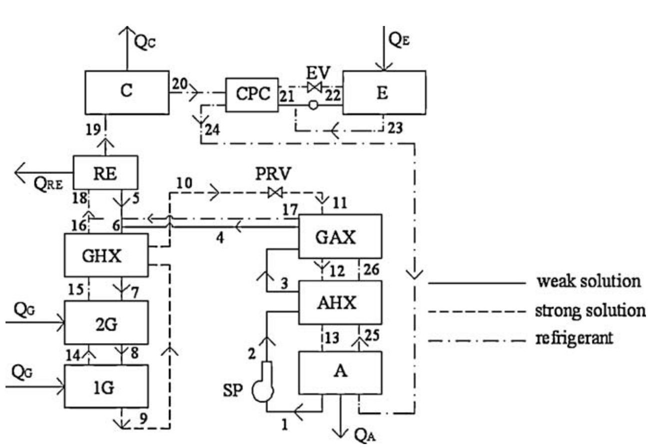

Fig. 3. Schematic of solar GAX cycle using ammonia–water solution pair [23].

Gomez et al. [26] evaluated an indirect-thermal oil fired, 3 TR GAX cycle, theoretically and experimentally. The COP of the system was found to be 0.58 with a generation temperature of 192 °C. An internal heat recovery of approximately 55% of the total heat supplied in the generator was obtained. The performance of the GAX absorption system integrated to a micro-gas turbine as a cogeneration system, was also simulated and it was found that the overall efficiency of the cogeneration system was 29 and 49% for cooling loads of 5 and 20 kW, respectively.

Zheng et al. [27] simulated a single stage ammonia absorption system and a GAX cycle, and reported that the COP and the exergy efficiency of the latter were 31 and 78% respectively higher than those of the former. Based on the concept of exergy coupling, the absorption cycle was divided into the heat pump and heat engine sub-cycles. By means of the energy grade factor – enthalpy diagram, the thermodynamic analysis of the two frameworks were studied, which showed that the exergy demand of the heat pump sub cycle in the GAX cycle was the same as that of a single stage cycle.

Priedeman et al. [28] developed a gas operated, 5 TR ammonia–water GAX system for residential and light commercial applications. The COP of the system was found to be 0.68 at a full load condition. Simulation was also carried out and the results of the experimentation were found to be in close proximity with the simulation results. An improvement in burner generator efficiency, pressure drop between the evaporator and pump inlet, and less heat recovery in GAX resulted in a better performance of the system.

Park et al. [29] developed an ammonia GAX absorption cycle that could supply both chilled and hot water, using a single hardware. The effect of the outlet temperature of hot water, and the split ratio (the ratio of the solution flow rate into a hydronically cooled absorber to the total flow rate of the weak solution from the GAX section of the absorber) of the solution on the cooling COP and heating COP were investigated. It was inferred that the cooling COP of the three modes was 60, 42 and 87%, respectively. Mode 1 gave a better result from the hot water supply point of view. It was recommended that the optimum UA values of the solution cooled absorber and hydronically cooled absorber for mode 3 should be less than those of mode 1.

Saravanan et al. [30] investigated the performance of a biomass heated GAX absorption cooling system of 40 TR cooling capacity. A maximum COP of 0.58 was obtained for a generator temperature of 120 °C and a sink temperature of 30 °C. Compared to the single effect absorption system, the COP of the GAX system was found to be 30% higher. A saving of about 70% of electrical energy was obtained compared to that of a vapour compression system of same capacity.

McGahey and Christensen [31] investigated the GAX absorption cycle by using a modular steady state simulation. An enhanced version of the simulation model developed by the Oak Ridge National Laboratory (ORNL) was used to model the complete absorption system, including an indoor gas-fired generator and an outdoor air to hydronic heat exchanger. The simulation model was used to optimize the system, based on the performance of the UA values of the heat exchangers.

Ozaki et al. [32] simulated an absorption heat pump by considering the factors that influence the performance, such as the evaporating temperature, condensing temperature, and the efficiency of the heat recovery heat exchangers. It is concluded that a 5 K decrease of temperature difference in the GAX heat exchanger increased the cooling by 5.5% and a maximum heating COP was obtained at a 4 K temperature difference in the GAX heat exchanger.

Erickson and Tang [33] investigated double lift waste heat GAX cycles (semi-GAX cycles) that utilize the internal heat exchange

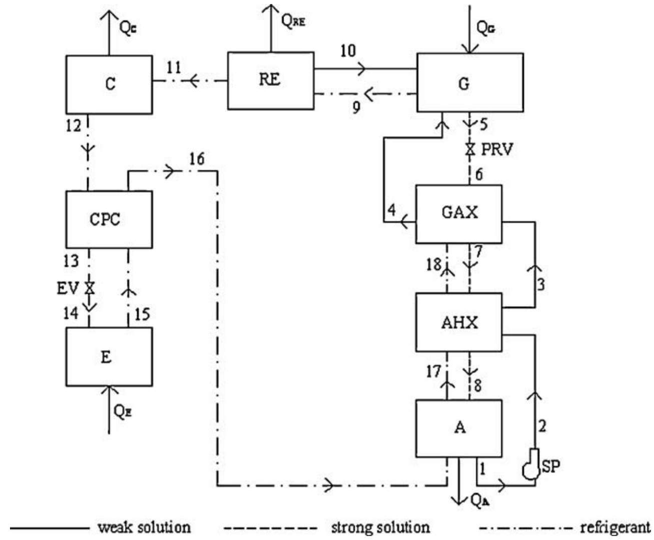

Fig. 4. Schematic of a GAX heat pump [34].

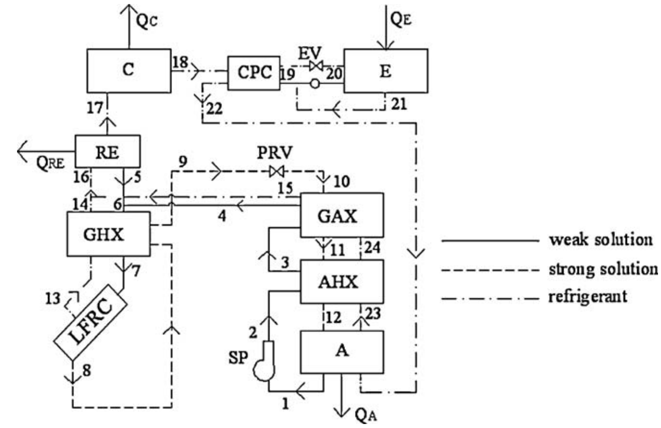

Fig. 5. Schematic of ammonia–water solar GAX refrigeration system with LFRC [38].

between the intermediate pressure absorber and the high pressure generator. An increase of 20% in the COP was obtained for the semi-GAX cycle when compared to the conventional double lift cycle, and the heat duty was found to be lower in the former.

Hanna et al. [34] analysed the GAX system as shown in Fig. 4, by employing the pinch point analysis technique. This technique has been commonly used in chemical process industries, where internal heat recovery plays a major role from the process design point of view. The study focused mainly on the processes in the cycle, and the advantage is the manner in which one could view the details of the internal processes of the cycle. By knowing the closeness of the state points of the heat recovery processes, an economic trade-off of the cycle components was achieved.

Kang and Kashiwagi [35] compared the performance of an ammonia–water GAX system (PGAX) and a single effect cycle for panel heating (PSE) applications. Due to the internal heat recovery in the GAX component, the COP of PGAX was higher than that of PSE. It was reported that the performance of an hydronically cooled absorber was more sensitive to the coolant temperature than that of the solution cooled absorber, and therefore, the effect of the UA ratio on the total COP of PGAX was higher than that of PSE. The parametric study revealed that the UA ratio could be used to select absorbers for heating capacities. The stream from the hydronically cooled absorber is split into the rectifier and the solution heat exchanger based on the split ratio and the optimum UA value occurred at a split ratio of 0.87.

Ng et al. [36] investigated experimentally a 2 TR gas-fired ammonia–water absorption chiller with a generator heat exchanger, an absorber heat exchanger and a regenerative GAX configuration. The COP of the system was about 0.8 at an operating condition of generator temperature of 200 °C, condenser temperature of 44 °C, absorber temperature of 41 °C and evaporator temperature of 5 °C.

Potnis et al. [37] simulated an ammonia–water GAX system for simultaneous heat and mass transfer for coexisting liquid film absorption and flow boiling desorption. The simulated temperature profiles were found to be close to the experimentally obtained profiles for different vapour and liquid flow rates. Also, the simulated values of the absorption side vapour phase flow rates were close to the experiment boundary condition. The simulation could predict the pinch point, the COP of the system as well as the vapour and liquid flow rates.

Velázquez et al. [38] presented a numerical simulation of the solar GAX cycle of cooling capacity 10.6 kW as shown in Fig. 5. The linear fresnel reflector concentrator which was used as an ammonia vapour generator was found to be technically feasible. The COP of the solar GAX cycle and the efficiency of the fresnel reflector concentrator were about 0.85 and 0.60, respectively. The numerical result also revealed that the availability of the solar beam radiation had a negligible effect on the COP of the system but a significant effect on the capacity of the fresnel reflector concentrator and the refrigeration cycle.

3.1.1. Inferences from the studies on simple GAX cycle

Several studies have been reported in the literature on simple GAX systems. The results from the prior work done clearly show that the performance of the system is 20–30% higher than that of a conventional simple absorption system, for the same operating conditions. Also, the GAX cycle has the advantage that it automatically gets converted into a single effect cycle, when the temperature overlap between the absorber and generator disappears. In spite of an enhanced improvement in the COP, the simple GAX system has certain drawbacks. First, the mismatch between the heat available in the absorber and the heat required in the generator. Second, the temperature overlap between the absorber and the generator only occurs at low lifts and not at high lifts. A majority of the results that are available are of theoretical investigations and the experimental findings are limited. The reason for limited experimental studies could be high manufacturing and operating costs due to additional pump that is required for secondary heat transfer fluids to transfer the heat from the absorber to the generator. It is obvious that more research is needed in future in order to validate the simulation model with the experimental findings.

3.2. Branched GAX cycle

Fig. 6 shows the schematic of the branched GAX cycle. The amount of heat supplied by the absorber to the generator is less than the requirement of the generator in a simple GAX cycle. This can be increased by increasing the mass flow rate in the absorber. This is accomplished in the branched GAX cycle by an additional solution pump. When the solution flow rate in the high temperature section of both the absorber and generator is increased, the high temperature section of the absorber supplies more heat to the low temperature section of the generator. At the same time, the heat requirement of the high temperature generator is increased, but the amount of heat that has to be supplied by the external source is decreased.

Engler et al. [39] performed the simulation of a gas-fired ammonia–water GAX system using an ABSIM modular program.

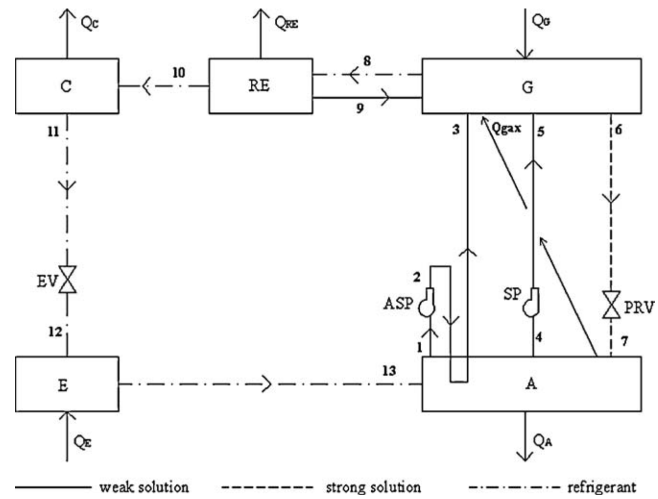

Fig. 6. Schematic of branched GAX cycle [12].

They analysed different configurations such as the conventional single effect cycle, the simple GAX cycle, the branched GAX cycle and the absorber heat exchange cycle. The influence of the components added at each stage on the cycle was investigated. The COP was found to be about 1.0 for the GAX cycle.

Erickson et al. [40] reported the results of a gas-fired branched GAX cycle heat pump as shown in Fig. 7 and showed that a cooling COP of 1.06 was obtained at a temperature effective lift (the difference between the evaporator temperature and the average of the condenser and absorber temperatures) of 38.9 °C and 4.2 TR of cooling capacity. For the same lift, the cycle cooling COP in the branched GAX was 1.04, and at an ambient condition of 35 °C, a cooling load of 4.5 TR was achieved at a cooling COP of 0.95. The performance of the branched GAX was marginally lower than that of the GAX cycle due to the sub-cooling of the absorbent liquid at the top and bottom of the GAX component.

Herold et al. [41] proposed a branched GAX cycle which addresses the main problem in the standard GAX cycle. It was found that the heat available in the absorber at each temperature level was not sufficient to meet the heat requirement of that temperature level in the generator. The branched GAX provided a better match between the hot and cold sides of the GAX heat exchanger, by increasing the solution flow rate in the high temperature end of the absorber. The performance of the branched GAX was higher than that of the standard GAX by 20%.

Zaltash and Grossman [42] demonstrated the potential of using ternary fluid mixtures for the advanced cycle by comparing the performance of the standard GAX and the branched GAX cycle

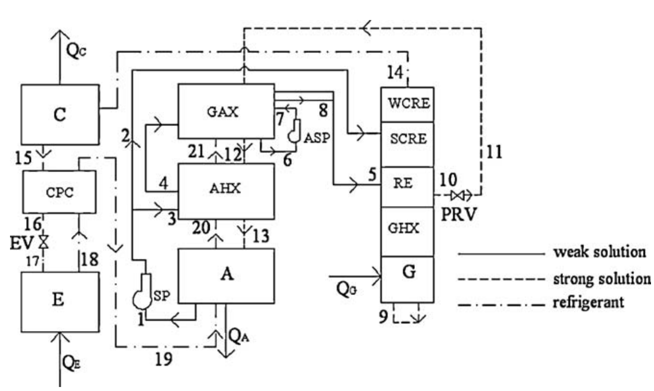

Fig. 7. Schematic of branched GAX prototype [40].

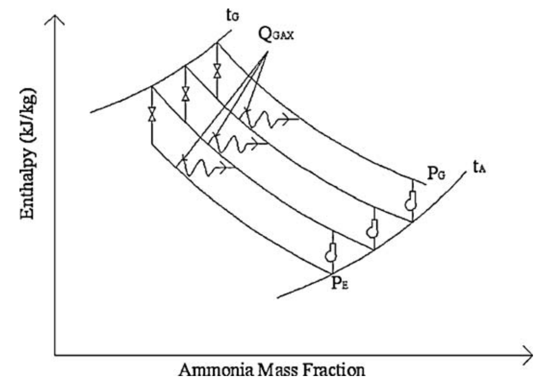

Fig. 8. Schematic of multi-branched GAX cooling system [43].

using ammonia–water and ammonia–water–lithium bromide mixture, by using ABSIM software. At a higher generator temperature of around 200 °C, the performance of the latter was higher than that of the former by 21%.

Stoicovici [43] introduced poly-branched regenerative GAX advanced cycles, which combine the advantages of the GAX, branched GAX, regenerative GAX and regenerative GAX with rectification heat recovery. Fig. 8 shows the schematic of the multi-branched GAX cooling system. In the branched GAX cycle, an additional solution pump is used to increase the mass flow rate in the absorber. The results highlighted the use of high solubility combinations at elevated temperatures, as well as increasing the boiling temperature and the number of stages. Compared to a double effect cycle, a two stage poly-branched regenerative cycle with rectification heat recovery was simple in construction and its thermal performance was 40% better. A three stage poly-branched regenerative GAX cycle had a COP 1.3 to 1.9 times higher for lifts (temperature difference between the condenser and the evaporator) varying between 68 and 47 °C.

3.2.1. Inferences from the studies on branched GAX cycle

From the reviewed literature, it is inferred that only a few attempts have been made by researchers, on branched GAX systems. The observations based on the limited studies show that the performance of the branched and poly-branched cycle was 10–20% and 40% respectively higher than that of the simple GAX cycle. The branched GAX cycle eliminates the mismatch between the heat available in the absorber and the heat required in the generator. Due to this, some amount of refrigerated vapour is generated in the GAX section of the generator, which reduces the external heat input requirement of the generator further. Apart from the conventional binary fluid mixture, Zaltash et al. [42] and Stoicovici et al. [43] employed ternary fluid mixtures of ammonia–water–lithium bromide, and found that the latter showed a better result than the former due to the increase in the temperature overlap range between the absorber and the generator. Compared to simple GAX system, the cost of the branched GAX system will be more due to the additional solution pump. However, the reduced heat load and heat transfer area of the absorber and the generator, would compensate partially for the increase in the cost.

3.3. GAX absorption compression cycle

The schematic of the GAX absorption compression cycle is shown in Fig. 9. In this cycle, the weak solution is pumped to the condenser pressure and introduced to the high temperature section of the absorber where it receives heat from the absorber and the refrigerant in it is boiled off in the generator. The strong solution flows back from the generator to the absorber. The

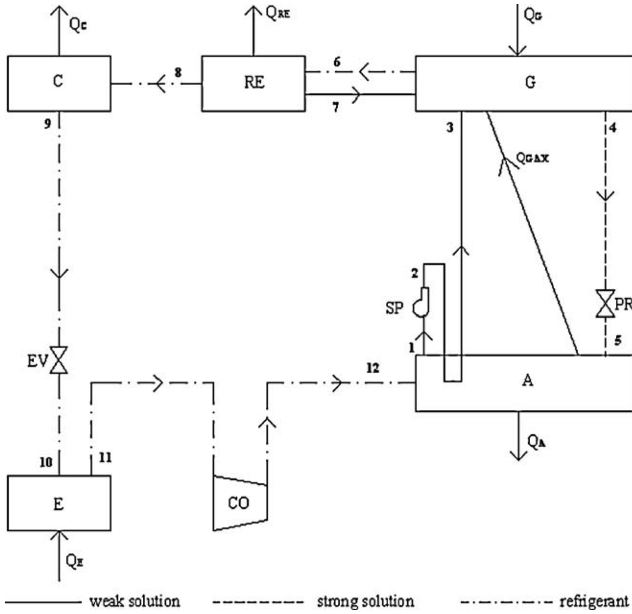

Fig. 9. Schematic of GAX absorption compression cycle [44].

generator and absorber temperature ranges partially overlap. This overlapped heat is internally transferred from the absorber to the generator. The high pressure refrigerant vapour after the rectification process in the rectifier enters the condenser and leaves as saturated liquid. The expansion valve reduces the pressure of the liquid refrigerant from the condenser pressure to the evaporator pressure. The liquid refrigerant then evaporates in the evaporator by absorbing the heat from the space being conditioned and the resulting low pressure saturated ammonia vapour enters the compressor, which is placed between the evaporator and the absorber. The compressor raises the absorber pressure higher than the evaporator pressure. In the absorber, the refrigerant vapour is absorbed by the strong solution returning from the generator and the cycle is repeated.

Ramesh Kumar and Udaya Kumar [44] simulated a GAX absorption compression cycle as shown in Fig. 9, operated with the ammonia–water working fluid pair. The degassing range (difference between the mass fraction of the weak and strong solutions) of the cycle was optimized for the maximum COP and the effect of the absorber pressure on the component heat duties were investigated. The hybrid GAX cycle showed an increases of 30% COP compared to that of the simple GAX cycle. It was reported that the hybrid cycle could be operated by utilizing low temperature energy sources.

Groll and Radermacher [45] simulated an ammonia–water DAHX system and reported that the internal heat exchange between the desorber and absorber resulted in a very low pressure ratio of about 70% lesser, when compared to that of the conventional ammonia refrigeration system and up to 62% lesser than that of the R-22 system. The cooling COP of the DAHX cycle was 10% higher than that of the conventional ammonia refrigeration system and 26% higher than that of an R-22 system for the same operating conditions.

Zhou and Radermacher [46] experimentally investigated the vapour compression cycle with a solution circuit and desorber/absorber heat exchanger. The working fluid employed was an ammonia–water mixture. For a temperature lift between 60 and 80 °C, a COP in the range of 1.2–1.8 was obtained and the cooling capacity range was found to be between 7 and 12 kW. The results were compared with those of a single stage and two stage cycle which revealed, that the two stage cycle had the highest temperature lift and lowest cooling COP. However, the single stage cycle had the highest cooling COP but the lowest temperature lift. The experimental results showed that when a bypass was introduced between the outlet of absorber I and the inlet of generator II, the sub-cooling decreased and the variation in the cooling COP was between 1 and 3% and the temperature lift increased by a maximum of 6 °C.

Ramesh Kumar and Udaya Kumar [47] simulated a GAX and GAX absorption compression cooler using ammonia–water, ammonia–lithium nitrate and ammonia–sodium thiocyanate as working fluids. The performance of the ammonia–lithium system was better than that of the other two working fluid pairs, in both configurations, at an optimum pressure ratio of 1.9, generator

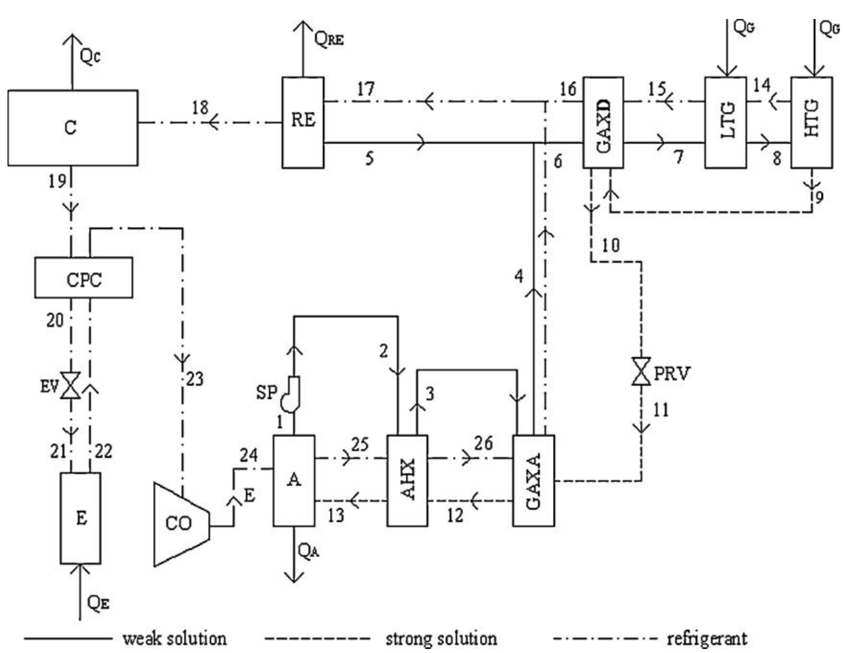

Fig. 10. Schematic of GAX absorption compression cooler [49].

temperature of 130 °C, condenser temperature of 45 °C, absorber temperature of 35 °C and evaporator temperature of 5 °C.

Ramesh Kumar and Udaya Kumar [48] studied the effect of the compressor pressure ratio on a 1 TR ammonia–water GAX absorption compression cooler. The effects of the generator, sink and evaporator temperatures on the performance of the cycle as a function of the pressure ratio were studied. The optimum COP corresponding to the optimum pressure ratio was found to be independent of the sink and evaporator temperatures, for a given value of generator and approach temperatures. The performance of the analysed cycle was nearly 25% higher than that of the standard GAX cycle.

Ramesh Kumar et al. [49] investigated the heat transfer modeling of an 11.5 kW GAX absorption compression cooler, as shown in Fig. 10. The influence of the UA value of the absorber and generator were analysed. At an operating condition of the minimum UA value of all the heat exchanging components, the maximum COP of the system was found to be around 1.2. The variation in the temperature of the cooling medium in the absorber was found to have a greater effect on the COP and capacity of the system than a variation in that of the condenser.

Kang et al. [50] developed four different advanced hybrid GAX cycles and carried out a parametric analysis. The development of the four cycles was: Type A for performance improvement, Type B for low temperature applications, Type C for the reduction of generator temperature and Type D for hot water temperature applications. The schematic of the A and B Type hybrid GAX cycles is shown in Fig. 11. The improvement in the COP of Type A was 24% higher than that of the simple GAX for the same operating conditions. In Type B, it was observed that at an evaporation temperature of −80 °C the COP was 0.3. The maximum generator temperature that could be reduced was 164 °C, and eventually this eradicates the corrosion problem that occurs at temperatures above 200 °C in the simple GAX. In Type D, the highest hot water temperature that could be obtained was 106 °C, which can be subsequently used for floor heating applications.

3.3.1. Inferences from the studies on the GAX absorption compression cycle

The observations based on the reviewed literature on the GAX absorption compression cycle clearly show that the performance of the GAX absorption compression system is higher than that of the simple GAX cycle by 10–30%. The simulation models developed by many researchers do not include a detailed heat exchanger analysis. However, Ramesh Kumar et al. [49] showed that the UA values of the absorber and high temperature generator have a significant impact on the cooling capacity and performance of the system. From the economic point of view, ammonia–lithium nitrate and ammonia–sodium thiocyanate are suitable alternatives to the conventional ammonia–water working fluid pair as the former eliminates the need for a rectifier. However, studies on the GAX absorption compression cycle with respect to the different absorbents for ammonia need further investigations, to exactly predict the best one. Further, the extent to which the absorber pressure can be increased in the GAX absorption compression cycle is limited because the additional power requirement for compressing the vapour should be less than the savings from the reduced heat requirement of the generator.

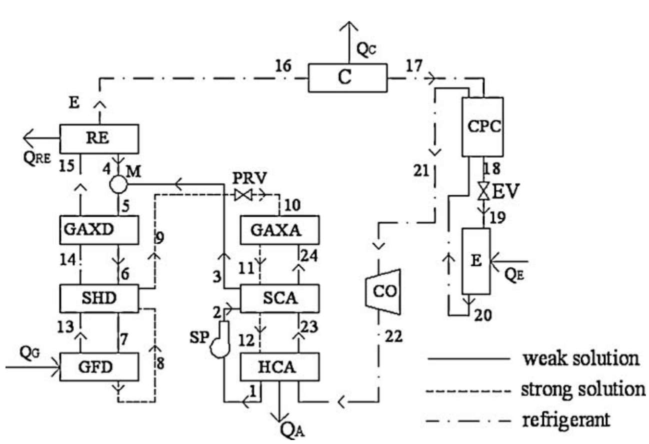

Fig. 11. Schematic of HGAX cycle [50].

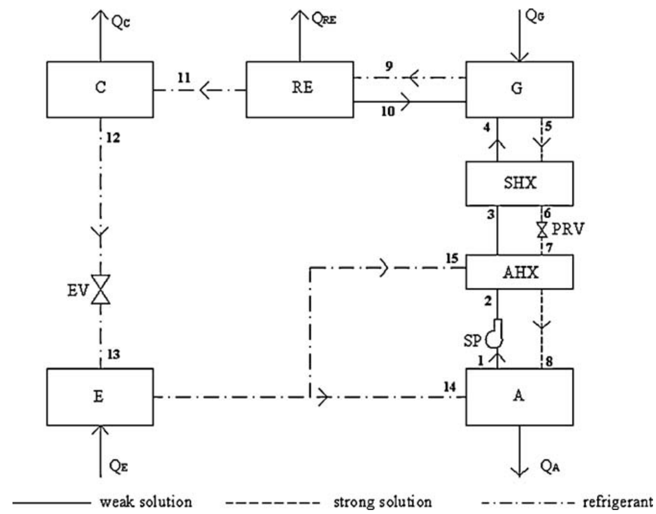

Fig. 12. Schematic of absorber heat recovery cycle [5].

3.4. Absorber heat recovery and other advanced cycles

Fig. 12 shows the schematic of the absorber heat recovery cycle. Similar to the simple GAX cycle, the absorber is divided into two sections. The low temperature section of the absorber rejects the heat to the ambient. But the high temperature section of the absorber is used to preheat the incoming weak solution by utilizing the heat of absorption, which results due to the partial absorption of the refrigerant vapour from the evaporator. Hence, the heat input to the generator is reduced causing the COP to increase.

Kandlikar [51] proposed an effective method of utilizing the heat of absorption to improve the system performance. The performance of the proposed system with the heat recovery absorber was found to be 10% higher than that of the conventional aqua ammonia absorption refrigeration system. The improvement in the COP of the system also reduced the cost by the effective utilization of solar energy which decreases the collector area. The author concluded that a detailed analysis has to be done in order to arrive at optimum design conditions.

Saghiruddin and Altamush Siddiqui [52] analysed the economic aspect and the performance study of the absorber heat recovery cycle as shown in Fig. 13, using NH_3–H_2O, NH_3–$LiNO_3$ and NH_3–$NaSCN$. The performance of the system improved by about 20–30% in the NH_3–H_2O mixture and by 30–35% in the NH_3–$LiNO_3$ and NH_3–$NaSCN$ mixtures. However, there was a considerable reduction in the energy costs also by about 10–25% in the NH_3–H_2O system and around 20–30% in the NH_3–$LiNO_3$ and NH_3–$NaSCN$ systems. The operating cost of the system was the lowest when bio-gas was used as the heat source compared to LPG.

Kaushik and Rajesh Kumar [53] showed that an absorber heat recovery cycle yields a higher COP compared to the conventional cycle at higher generator temperatures. Water lithium bromide was used as the working fluid pair. They also revealed that the addition of the absorber heat exchanger does not increase the heat

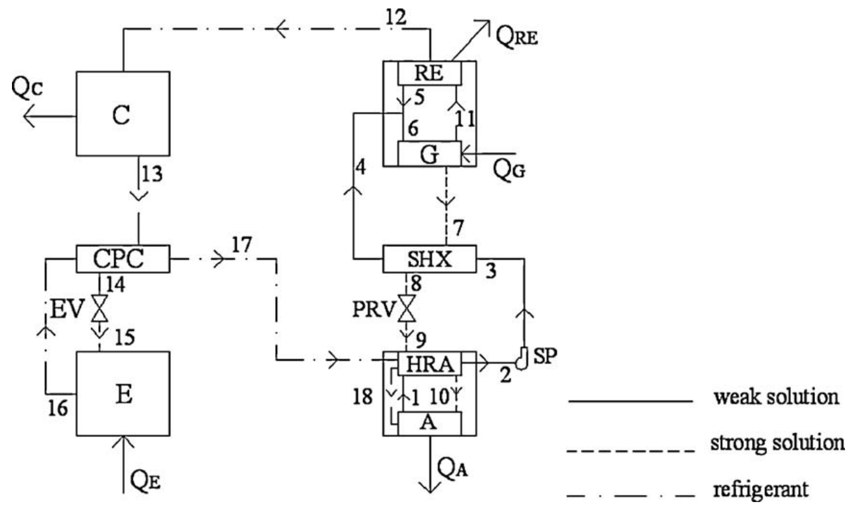

Fig. 13. Schematic of absorption refrigeration system with heat recovery absorber [52].

exchanger area because it reduces the size of the absorber and generator. However, the system was restricted to a limited range of operating conditions due to the crystallization problem associated with the working fluid pair.

Ozaki et al. [54] compared the performances of the ammonia–water advanced cycles, a GAX cycle, a hybrid cycle (a combination of a basic cycle and a mechanical compressor) and a GAX hybrid cycle. The GAX hybrid cycle was found to be more efficient in the cooling mode and the performance of all the cycles was almost similar in the heating mode.

Kang et al. [55] proposed an advanced GAX cycle for low temperature applications and obtained an evaporator temperature of −50 °C. Kang et al. [56] developed an advanced GAX cycle namely, Types A, B and C, as shown in Fig. 14, to utilize the waste heat, and studied the parametric analysis of the effects of the waste heat source temperature and the outlet temperature of the gas-fired generator. In the Type A cycle, the solution heated desorber of the standard GAX is replaced by a waste heat exchanger; an extra heat exchanger is added to the standard GAX in Type B, and in Type C the solution heated desorber is placed between the rectifier and the GAX desorber to transfer the extra heat of the strong solution to the desorber column. It was found that the effect of the waste heat temperature on the performance of the system was negligible for a given gas-fired generator outlet temperature. The corrosion problem in the standard GAX cycle at temperatures higher than 200 °C could be solved by employing the WGAX. Type A was better from the view point of the GAX effect, whereas, Type B was better from the point of view of the exergy loss. It was recommended that sub-cooling is necessary to improve the COP in WGAX systems.

Sabir et al. [57] analysed the performance of a novel GAX-resorption heat driven refrigeration cycle. The novel system was as simple as that of a single effect cycle and the performance was

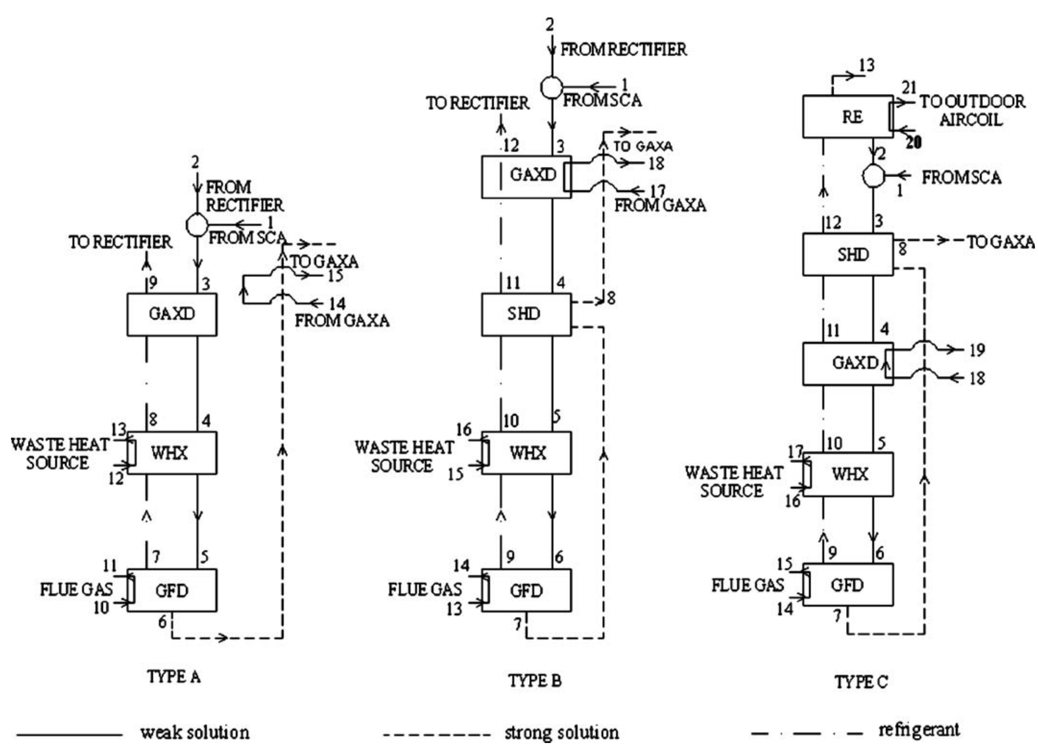

Fig. 14. Schematic of WGAX cycle [56].

Table 1
Summary of the investigations on different types of GAX cycles.

S. no.	Author	T/EXP	Heat source	Cycle	Working fluid	Cooling method	Applications
1	Priedeman and Christensen [21]	T & EXP	Natural gas	GAX	NH_3–H_2O	Air	Residential and light commercial
2	Velázquez and Best [23]	T	Natural gas and solar energy	GAX	NH_3–H_2O	Air	Space conditioning
3	Garimella et al. [24]	T	Natural gas	GAX	NH_3–H_2O	Air	Heating and cooling
4	Grossman et al. [25]	T	Natural gas	GAX	NH_3–H_2O	Air	Domestic and light commercial
5	Gomez et al. [26]	T & EXP	Thermal oil	GAX	NH_3–H_2O	Air	Air conditioning
6	Priedeman et al. [28]	T & EXP	Natural gas	GAX	NH_3–H_2O	Air	Residential and light commercial
7	Park et al. [29]	T	Gas	GAX	NH_3–H_2O	Water	Hot water and chilled water
8	Saravanan et al. [30]	EXP	Biomass	GAX	NH_3–H_2O	Water	Dairy
9	McGahey and Christensen [31]	T	Natural gas	GAX	NH_3–H_2O	Air	Light commercial
10	Kang and Kashiwagi [35]	T	Flue gas	GAX	NH_3–H_2O	Air	Panel heating
11	Ng et al. [36]	EXP	Gas	GAX	NH_3–H_2O	Air	–
12	Velázquez et al. [38]	T	Solar energy	GAX	NH_3–H_2O	Air	–
13	Engler et al. [39]	T	Natural gas	Branched GAX	NH_3–H_2O	Air	Domestic and light commercial
14	Erickson et al. [40]	T & EXP	Gas	Branched GAX	NH_3–H_2O	Air	–
15	Herold et al. [41]	T	–	Branched GAX	NH_3–H_2O	Air	Heating and cooling
16	Zaltash and Grossman [42]	T	–	Branched GAX	NH_3–H_2O, NH_3–H_2O–LiBr	–	–
17	Stoicivici [43]	T	–	Poly-branched GAX	NH_3/H_2O–LiBr	–	–
18	Ramesh Kumar and Udaya Kumar [44]	T	–	Absorption–compression GAX	NH_3–H_2O	–	Air conditioning
19	Zhou and Radermacher [46]	EXP	Hot water	Absorption–compression GAX	NH_3–H_2O	Water	–
20	Ramesh Kumar and Udaya Kumar [47]	T	–	Absorption–compression GAX	NH_3–H_2O, NH_3–$LiNO_3$, NH_3–NaSCN	–	Space conditioning
21	Ramesh Kumar and Udaya Kumar [48]	T	–	Absorption–compression GAX	NH_3–H_2O	–	Low temperature
22	Ramesh Kumar et al. [49]	T	–	Absorption–compression GAX	NH_3–H_2O	Water	Low temperature
23	Kang et al. [50]	T	Flue gas	Absorption–compression GAX	NH_3–H_2O	Air	Low temperature and hot water
24	Kandlikar [51]	EXP	Solar	Absorber heat recovery	NH_3–H_2O	Air	–
25	Saghiruddin and Altamush Siddiqui [52]	T	–	Absorber heat recovery	NH_3–H_2O, NH_3–$LiNO_3$ NH_3–NaSCN	–	–
26	Kaushik and Rajesh Kumar [53]	T	–	Absorber heat recovery	H_2O–LiBr	Water	Air conditioning
27	Ozaki et al. [54]	T	–	Advanced GAX	NH_3–H_2O	–	Heating and cooling
28	Kang et al. [56]	T	Flue gas/waste heat	Advanced GAX	NH_3–H_2O	Air	Waste heat utilization
29	Sabir et al. [57]	T	Waste heat/renewable energy	GAX-resorption	H_2O–LiBr	Water	–
30	Erickson and Anand [59]	T	Waste heat	VX GAX	–	–	Industrial

found to be sensitive to the inlet temperature of the cooling/chilled water. The COP of the system was better than that of the conventional single effect vapour absorption and resorption cycles, but less than that of the GAX cycles. However, it was anticipated that, a wide range of water temperatures, and mass and heat transfer effectiveness would result in a better performance than that of a simple GAX system.

Rane and Erickson [58] presented a patented three pressure GAX cycle which addresses the problem that at high temperature lift greater than 60 °C, there is no GAX temperature overlap. At these higher temperature lifts, the three pressure GAX cycle gives a better COP compared to that of the conventional single effect system. It was found that, for a temperature lift of 85 °C, the analysed GAX cycle prevents 10% reduction in the COP due to the rectification losses in a conventional cycle.

Erickson and Anand [59] developed a VX GAX cycle similar to the branched GAX. It was a three pressure cycle that incorporated the heat of absorption into both the high pressure and intermediate pressure generators. The performance of the new cycle was better than that of the conventional cycle. The economic analysis indicates that the VX GAX cycle provides commercially viable industrial refrigeration operated by prime fuel or waste heat.

Anand and Erickson [60] examined the characterization of the absorption cycle performance in terms of cycle lift (difference between the condenser and evaporator temperatures) and revealed that the absorption cycle performance was dependent on the absorption compressor and absorber temperature. Further, the variation in the absorber temperature affected the overall system performance. Variations of the effective lift curve, such as those observed for the basic GAX and VX GAX cycles at low lifts, indicate the limitations in the performance of the system. The performance data of the actual system were presented for the VX GAX cycle heat pump, and the concept of the effective lift was validated.

3.4.1. Inferences from the studies on absorber heat recovery and other advanced cycles

The performance of the absorber heat recovery cycle is higher than that of the conventional single effect system by at least 10%. Apart from the ammonia–water working fluid pair, water lithium bromide, ammonia–sodium thiocyanate and ammonia–lithium nitrate working fluids have been employed by some researchers in the absorber heat recovery cycle. The COP of the regenerative GAX system and advanced GAX cycle is much better compared to that of the simple GAX cycle. The advanced GAX cycles such as WGAX and LGAX have been developed for the utilization of waste heat and low temperature applications, respectively. The development of the vapour exchange GAX cycle addressed the problem of negligible temperature overlap between the high temperature end of the absorber and the low temperature end of the generator, at a higher temperature lift. However, the limitations on the performance of the different GAX cycles in terms of effective lift needs to be addressed to help the designers to improve the system performance further. Table 1 gives a summary of the investigations on different types of GAX cycles such as the simple GAX, the branched GAX, the absorption compression GAX, the absorber heat recovery system and the advanced GAX. It is inferred from the table that most of the different types GAX systems employs air as the cooling medium. The air-cooled absorber and condenser eliminate the need for a cooling tower and cooling water pump that are required for water cooled systems and hence reduce the operating and maintenance costs.

4. Conclusion

The present review is a comprehensive one on the research progress made in the GAX systems. The salient feature that can be drawn from the review is that GAX systems have shown promising results in enhancing the performance of the system. The COP of the most advanced GAX cycle can be raised up to 40% higher than that of the conventional single effect systems. Also, GAX systems have the ability to operate over a wide concentration difference with respect to ammonia–water mixture. In addition to ammonia–water, a few alternative working fluid mixtures have been studied both from the technical and economic points of view. A reduction in the energy cost of about 25% in the ammonia–water cycle and 30% in the ammonia–sodium thiocyanate and ammonia–lithium nitrate cycles with heat recovery absorber has been achieved, when bio-gas was used as a heat source.

Based on the promising results presented in the literature so far, it seems that the research activities on GAX systems will increase in the future. More experimental investigations are essential in order to have a detailed comparison on the performance of the system. The possibility of an advanced cycle is suggested, which utilizes the GAX both on the high pressure and low pressure sides and also employing an additional heat exchanger to recover the heat from the flue gas would further improve the COP of the system.

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